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2500 KW SHIP SERVICE TURBINE GENERATOR CASING WELDED INCONEL PLUG FAILURE AND REPAIR ANALYSIS

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ABSTRACT
Six of seven US Navy Wasp Class (LHD) ships have 2500 KW Ship Service Turbo Generator (SSTG) steam turbine casings that were mistakenly manufactured with in-place first stage balancing holes in both the inboard and outboard sides of the upper casing half. These holes were intended for in-place balancing of the turbine rotor; however, the US Navy did not request the access holes since in-place balancing is typically not accomplished on in-service surface ship SSTGs. To correct the mistake, the OEM, developed a procedure to weld plugs into the holes. Unfortunately, cracks developed in the plug weld heat affected zones (HAZs) on many of the in-service units. Some cracks propagated entirely through the plug and leaked steam in service. A failure analysis determined that the original plug (Inconel X750) should have received post weld heat treatment (PWHT) to avoid embrittlement and the subsequent cracking of the HAZ. If PWHT was not to be accomplished, an alloy such as Inconel 600 should have been selected. It is noted that PWHT risks warping the casing and cannot be performed in-place. Inconel 600 repair plug installations were performed in-place, permitting a fast repair turnaround time, which allowed the affected ships to meet operational schedules.

To evaluate the repair integrity, the US Navy reviewed the failure analysis data and repair procedure and performed a Finite Element Analysis (FEA) and Fracture Analysis. Various "improved plug" designs were also studied in parallel to determine if a different geometry plug would better resist future cracking. During repairs, minor radial cracks were discovered in the welding "inlay" originally installed between the casing and plug weld. Because the inlay had to be fully preserved to avoid complex and time consuming additional repairs to the casing including PWHT, minor cracks were left in place and consumed by the new weld

An important objective of this effort was to prove that if any cracking ever reoccurred only minor steam leakage would result. The leakage would be apparent to the operators long before there was potential for the plug to fail catastrophically; moreover, a "leak-before-break" determination was requested to be proven and validated.

INTRODUCTION
During 2008 post-overhaul steam testing on an LHD, minor steam leakage was discovered coming from one of the SSTGs. A visual inspection and dye penetrant (PT) inspection identified circumferential cracking on both inboard and outboard upper turbine casing plugs. All cracks occurred in the HAZ of the plug adjacent to the installation weld. Figures 1, 2, and 3 show examples of the cracks.

During manufacture of the turbine casing, the OEM installed the plugs into the 1-1/4 Cr-1/2 Mo (Cr-Mo) turbine casing by weld-depositing an inlay of Inconel 600 alloy, followed by shielded metal arc welding (SMAW) of the Inconel X-750 plug using a nickel base alloy filler material. The failure was investigated by reference (1), which concluded that inter-granular fracturing was the direct mode of failure, likely caused by embrittlement from lack of PWHT. An in-place repair procedure, reference (2), was developed and performed by Norfolk Naval Shipyard (NNSY) which removed the current Inconel X-750 plug and replaced it with an Inconel 600 plug to eliminate the HAZ embrittlement problem. Following the first repair, visual and PT inspections of all LHD SSTG casing plugs were performed, as directed by Naval Message, reference (3). Repairs were immediately performed on SSTG casings that leaked steam. All Inconel X-750 plugs were eventually replaced with Inconel 600 plugs by utilizing the NNSY developed repair process.

During these repairs, issues arose regarding preservation of the plug hole inlay and minor radially oriented cracks discovered after removal of the original plug. Normally, US Navy welding procedures do not allow welding over cracks, no matter how minor. However, removal of the cracks in this instance would require complete removal and restoration of the welding inlay, followed by PWHT. PWHT requires removal of the casing due to the risk of warpage, a 3-month process. A

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14. ABSTRACT

Six of seven US Navy Wasp Class (LHD) ships have 2500 KW Ship Service Turbo Generator (SSTG) steam turbine casings that were mistakenly manufactured with in-place first stage balancing holes in both the inboard and outboard sides of the upper casing half. These holes were intended for in-place balancing of the turbine rotor; however, the US Navy did not request the access holes since in-place balancing is typically not accomplished on in-service surface ship SSTGs. To correct the mistake, the OEM, developed a procedure to weld plugs into the holes. Unfortunately, cracks developed in the plug weld heat affected zones (HAZs) on many of the in-service units. Some cracks propagated entirely through the plug and leaked steam in service. A failure analysis determined that the original plug (Inconel X750) should have received post weld heat treatment (PWHT) to avoid embrittlement and the subsequent cracking of the HAZ. If PWHT was not to be accomplished, an alloy such as Inconel 600 should have been selected. It is noted that PWHT risks warping the casing and cannot be performed in-place. Inconel 600 repair plug installations we reperformed in-place, permitting a fast repair turnaround time, which allowed the affected ships to meet operational schedules. To evaluate the repair integrity, the US Navy reviewed the failure analysis data and repair procedure and performed a Finite Element Analysis (FEA) and Fracture Analysis. Various improved plug designs were also studied in parallel to determine if a different geometry plug would better resist future cracking. During repairs, minor radial cracks were discovered in the welding inlay originally installed between the casing and plug weld. Because the inlay had to be fully preserved to avoid complex and time consuming additional repairs to the casing including PWHT, minor cracks were left in place and consumed by the new weld. An important objective of this effort was to prove that if any cracking ever reoccurred only minor steam leakage would result. The leakage would be apparent to the operators long before there was potential for the plug to fail catastrophically; moreover, a leak-before-break determination was requested to be proven and validated.

15. SUBJECT TERMS

Inconel x750 600 Chrome-moly Casting Inconel weld repair system Steam Turbine Generator SSTG

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Fracture Analysis was performed to determine the projected reliability and service life of repairs with welded over cracks. See Figure 3.

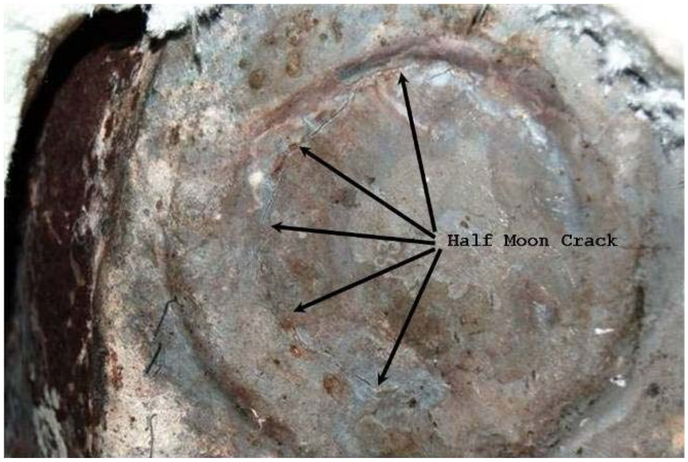


FIGURE 1: CIRCUMFERENTIAL CRACKING IN PLUG

FIGURE 2: CIRCUMFERENTIAL CRACKING IN PLUG

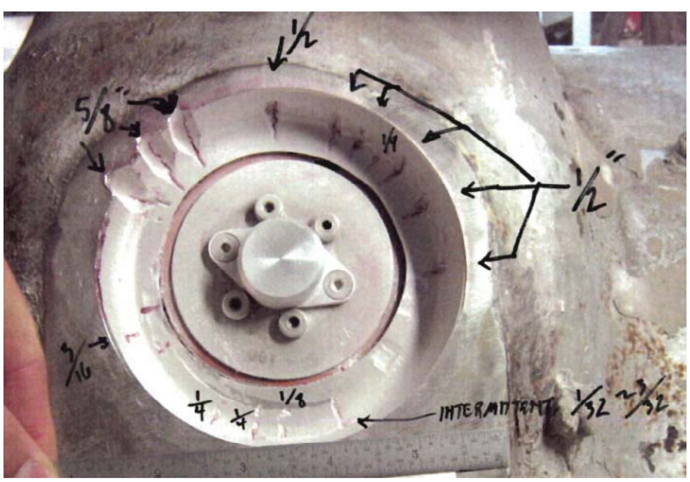


FIGURE 3: RADIAL CRACKING IN INLAY

In summary, this paper discusses the following objectives:

1. Review and comment on the plug failure analysis, reference (1) and the repair procedure, reference (2).

2. Perform a stress analysis using FEA to determine the integrity of the repair.

3. Study new plug designs that reduce stress concentrations in the HAZ.

4. Perform a fracture analysis on a model plug with typical weld inlay inclusions.

FAILURE ANALYSIS AND REPAIR PROCEDURE REVIEW

Per reference (4), an analysis of the original welded plug installation joint was developed from the NNSY repair process and original failure analysis. The weld joint analysis concluded that two mechanisms resulting from the welding process were the most likely cause of the cracking. These are strain age cracking and hot cracking. Strain age cracking can be minimized by:

1. Choose a less susceptible alloy that does not harden by precipitation heat treatment or choose an alloy that ages in a much more sluggish fashion.

2. Minimize residual and thermally induced stresses.

3. Minimize heat input while welding. If the welding temperature was too high, the heat could have resulted in partial melting of the grain boundaries directly adjacent to the fusion line. This, coupled with a heat excursion in the application, may have triggered the problem.

Hot cracking can be prevented by:

1. Similar to prevention of strain age cracking, control the heat input during welding.

2. Minimize the amount of certain minor elements when specifying this material type. Minor elements include those such as sulfur, phosphorous, lead, boron and zirconium.

NNSY Weld Repair Procedure 5.57/09 called out by reference (1) contained measures needed to reduce the potential for cracking. Improved plug and filler materials, and the gas-tungsten arc welding process (GTAW) were specified. Heat input was carefully controlled. The following changes to the procedure were recommended by reference (3):

1. Change the allowable minimum thickness of the remaining Inconel clad on the turbine casing from 3/32 inch to 3/16 inch.

2. Change the minimum radial distance between the new weld and the interface between the existing Inconel inlay and the chrome-moly turbine casing from 1/16 inch to 3/16 inch.

3. Add a step to positively assure all Inconel X-750 that diluted into the existing inlay has been removed prior to welding. An acid etch using 50/50 HCl/H_2O_2 etchant was recommended.

FINITE ELEMENT ANALYSIS

The purpose of FEA was to evaluate the mechanical/thermal stress effect on the casing plug and installation weld. High stress concentration was considered a driver for plug crack initiation. The analyzed stress value was compared with material design data to assess the possibility of crack initiation. The FEA is summarized here.

3D CAD Model Construction

3D CAD drawings of the turbine components were constructed using Solidworks. The first step was to review technical drawings of the turbine casing/plug and study the geometry of the components. Detailed plug dimensions and weld arrangement are shown on Figures 4 and 5. Figure 4 is a sketch with dimensions of the Inconel 600 repair plug.

As presented on Figure 5, a nickel base alloy inlay was deposited on the turbine casing base metal before the plug is welded. The Inconel X-750 plug was then welded to the inlay by the SMAW process using a nickel base alloy covered weld electrode. Specified electrodes in the OEM Weld Procedure were MIL-4N1A or MIL-8N12 of MIL-E-22200/3.

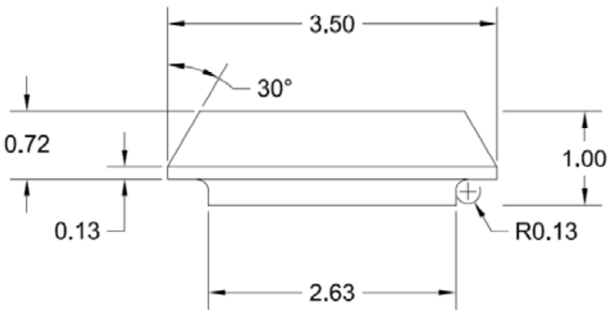


FIGURE 4: INCONEL 600 REPAIR PLUG

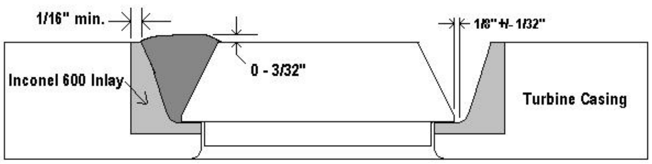


FIGURE 5: TURBINE CASING / PLUG WELD ARRANGEMENT

The 3D model was constructed as shown in Figure 6. The section of the turbine casing around the plug weld inlay HAZ was modeled and studied.

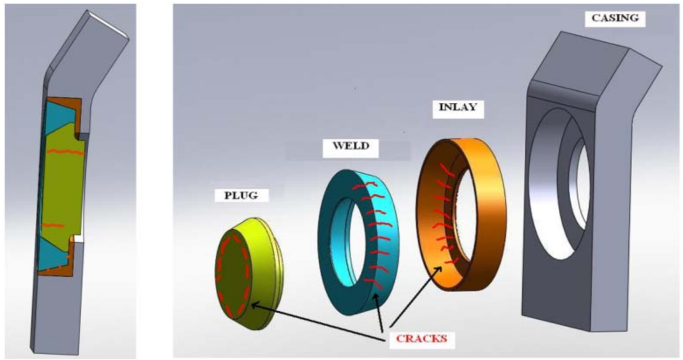


FIGURE 6: CROSS SECTIONAL VIEW (L) AND EXPLODED VIEW (R) OF THE TURBINE CASING / PLUG MODEL

Assigning Material Properties and Constraints

Before the finite element model of the repair could be analyzed, component material properties had be assigned. The turbine casing base metal is Chromium Molybdenum Alloy Steel (MIL-C-24707/2 or ASTM A217, grade WC6). The inlay is MIL-4N1A or MIL-8N12 of MIL-E-22200/3. The following items were changed from the original design: The turbine plug is now hot worked and annealed Inconel 600 bar (MIL-N-23229). The final weld layer that filled the gap between the plug and inlay is now nickel base alloy (MIL-RN82 rod of MIL-E-21562).

As a design constraint, four edges of the turbine casing were fixed, while the faces of the casing were assigned as "slider". The slider constraint allows the faces to slide in the x and y direction parallel to the face but not in the z direction, which is perpendicular to the face. An evenly distributed pressure of 280 PSI (maximum steam pressure exerted on the area while turbine is in operation) was applied on the inner surface of the turbine casing and plug (See Figures 7, 8, and 9 for a graphic presentation of design constraint).

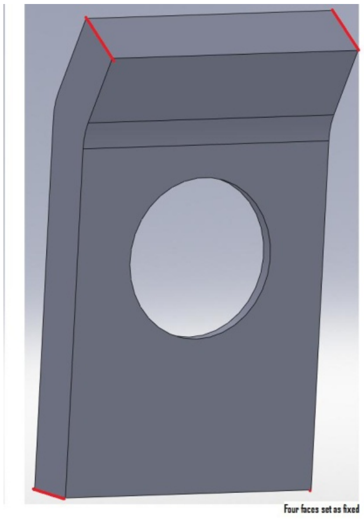


FIGURE 7: FOUR EDGES SET AS "FIXED"

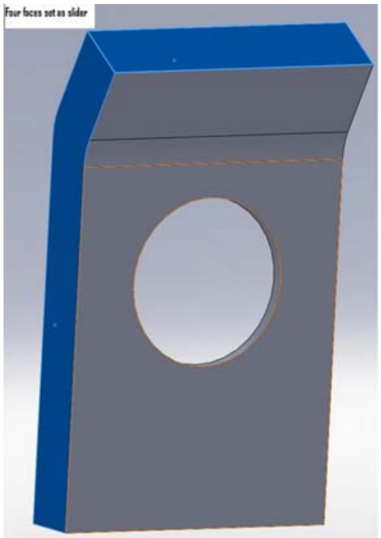


FIGURE 8: FOUR FACES SET AS "SLIDER"

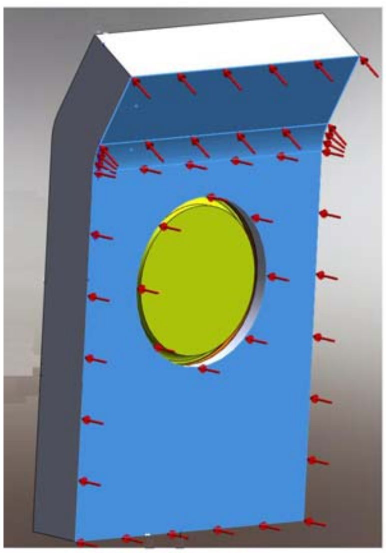


FIGURE 9: PRESSURE APPLIED ON INNER SURFACE

Meshing Process

The meshing process divided the model parts into many small elements. The elements can be refined in the area of interest to give a more accurate result. Overly refined mesh will result in lengthy calculation time and could distort the result. Therefore, the key was to optimize the element number to strike a balance between accuracy and calculation time. After the meshing process is completed, the FEA result can be obtained (See Figure 10 for an example of meshing process).

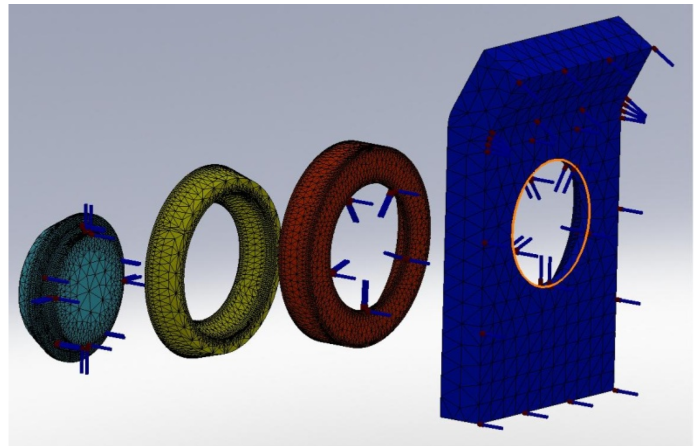


FIGURE 10: FEA MESHING PROCESS

FEA Mechanical Stress Result

The FEA stress plot generally indicated that pressure loads resulted in nominal stresses, 6000 PSI maximum. The highest stresses were concentrated at the underside of the plug. This finding could be significant when thermal stress is superimposed on the mechanical stress in the next phase of the stress analysis High stress was also indicated on the four edges of the turbine casing. This result was expected since the four edges were “fixed.” However, the high stress zone on the turbine casing does not affect the study since it was far enough away from the plug and weld. (See Figure 11 for a general representation of the FEA stress plot).

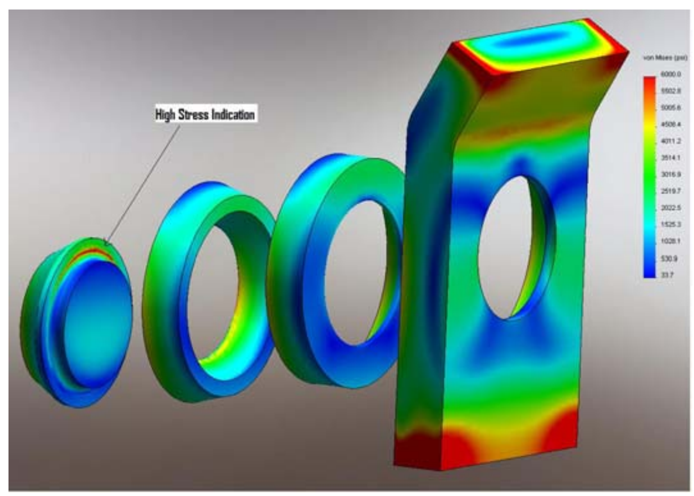


FIGURE 11: FEA STRESS PLOT RESULT

FEA Thermal Stress Study

Thermal stress is considered as a major contributor to fatigue growth once the crack is initiated. Cyclic thermal stress loading could cause accelerated defect propagation under certain conditions. To ensure the full thermal stress effect is captured, half of the upper turbine casing was modeled (See Figure 12).

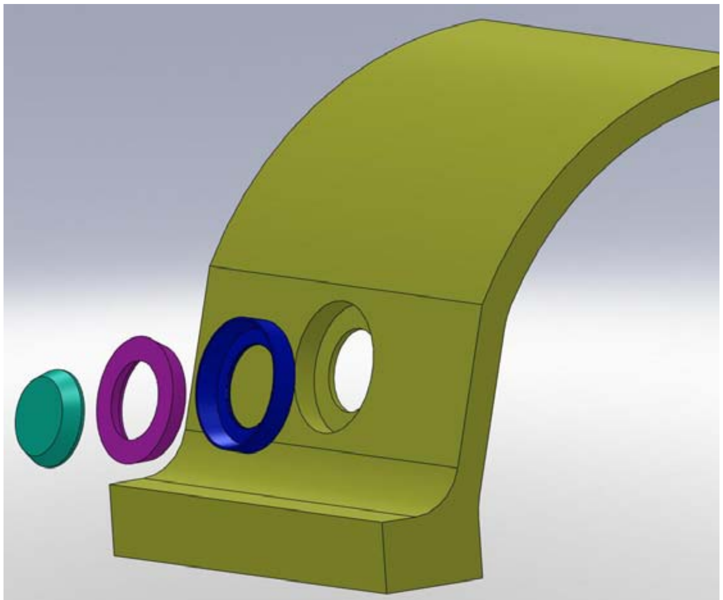


FIGURE 12: FEA MODEL OF TURBINE CASING

A question might be asked about the reason to include a larger casing area in the model. The previous analysis studied the mechanical stress on the plug. Unlike thermal stress, mechanical stress can be accurately modeled in a localized area. As for thermal stress, it is mainly caused by thermal expansion and the effect may be more global than local. The larger model required more elements to calculate and computer power to process while the smaller model used for the mechanical stresses runs faster, thus saving analysis time.

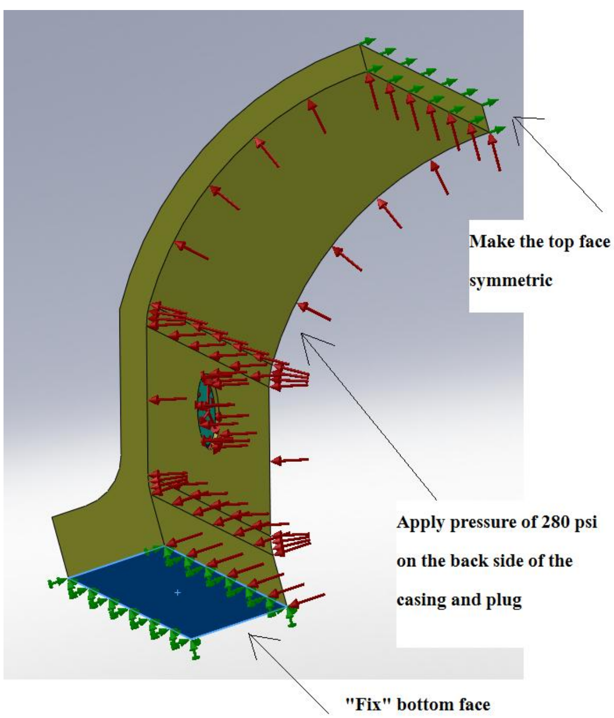


FIGURE 13: FEA MODEL CONSTRAINT

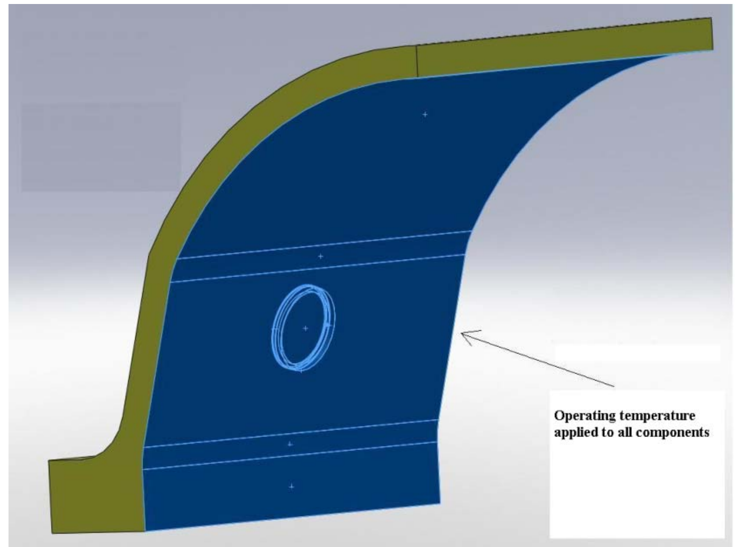


FIGURE 14: FEA THERMAL LOAD

After the 3D CAD model was generated, material properties and constraints were assigned (See Figures 13 and 14). A maximum pressure of 280 PSI was applied on the back side of the turbine casing. The bottom of the casing was "fixed" to restrain model movement. Since only half of the upper casing was modeled, a symmetrical condition had been applied to mirror the non-model half of the casing. For steady-state thermal conditions, the entire structure was assumed to be at uniform temperature. For the thermal stress analysis, four turbine loads were studied, shown in Table 1:

TABLE 1: DESIGN TEMPERATURE AND PRESSURE FOR VARIOUS TURBINE LOADS

Load	25 %	50%	75 %	100 %
Temperature	646 °F	696 °F	715 °F	743 °F
Pressure	86 PSI	173 PSI	210 PSI	280 PSI

The above values are the design temperature and pressure from the SSTG technical manual. The mechanical properties of the components (Plug, Inlay, Filler and Casing) are shown in
Table 2 and 3. Nickel-based component properties were obtained from reference (5).

TABLE 2: MECHANICAL PROPERTIES OF COMPONENTS

Component Properties	Modulus (PSI)	Density (lb/in^3)	Poisson's Ratio	Thermal Expansion Coefficient	Yield
Plug (Inconel 600)	3.11e7	0.306	0.327	Table 3, left column	31 KSI
Inlay and Filler Welds (MIL-4N1A, MIL-8N12, or MIL-RN82)	3.11e7	0.306	0.327	Table 3, center column	55 KSI
Casing (1-1/4Cr-1/2Mo Steel)	3.07e7	0.286	0.291	Table 3, right column	40 KSI

TABLE 3: COEFFICIENTS OF THERMAL EXPANSION OF COMPONENTS

Coefficient of Thermal Expansion (10^{-6}in/in °F)			
Temperature (°F)	Plug (Inconel 600)	Weld Metal (MIL-RN82)	Casing (1-1/4Cr-1/2Mo Steel)
70	5.8		
100			6.389
200	7.4	6.7	6.346
400	7.7	7.6	6.818
600	7.9	7.9	7.233
800	8.1		7.648

The solid model geometry was imported into ANSYS mechanical FEA software and meshed. Obtaining detailed results around certain components required mesh refinements around the plug, inlay, and filler. With all the refinements, the model contained approximately 174,000 nodes. The appropriate material properties are assigned to the corresponding component in the model (See Tables 2 and 3).

Thermal Stress Analysis Finding

Thermal stress analysis was conducted on the casing plug when the turbine is operating at 25%, 50%, 75% and 100% loads. The entire structure is at the same temperature. The thermal stress is created because the nickel-based plug and weld metal have a higher coefficient of thermal expansion than the steel turbine casing. The thermal and pressure stresses are then combined. Summary tables were generated for each load condition. The tables listed the four components and compare their maximum stresses with their yield and tensile stresses. If the maximum stress were to exceed the yield stress, cracking could potentially propagate quickly. Steady State Analysis results are tabulated below in Tables 4, 5, 6, and 7:

TABLE 4: STRESS RESULT OF TURBINE AT 25% LOAD

25% Load Case Temperature of 646 °F, pressure of 86 PSI			
Component	**Maximum Von Mises Stress**	**Yield Stress**	**Tensile Stress**
Plug (Inconel 600)	18 KSI	31 KSI	91 KSI
Casing (Cr-Mo Steel)	14 KSI	40 KSI	70 KSI
Filler Weld (MIL-RN82)	16 KSI	55 KSI	80 KSI
Inlay Weld (MIL-4N1A or MIL-8N12)	11 KSI	55 KSI	80 KSI

TABLE 5: STRESS RESULT OF TURBINE AT 50% LOAD

50% Load Case Temperature of 696 °F, pressure of 173 PSI			
Component	**Maximum Von Mises Stress**	**Yield Stress**	**Tensile Stress**
Plug (Inconel 600)	17 KSI	31KSI	91 KSI
Casing (Cr-Mo Steel)	13 KSI	40 KSI	70 KSI
Filler Weld (MIL-RN82)	15 KSI	55KSI	80 KSI
Inlay weld (MIL-4N1A or MIL-8N12)	9 KSI	55KSI	80 KSI

TABLE 6: STRESS RESULT OF TURBINE AT 75% LOAD

75% Load Case Temperature of 715 °F, pressure of 210 PSI			
Component	**Maximum Von Mises Stress**	**Yield Stress**	**Tensile Stress**
Plug (Inconel 600)	17 KSI	31 KSI	91 KSI
Casing (Cr-Mo Steel)	13 KSI	40 KSI	70 KSI
Filler Weld (MIL-RN82)	15 KSI	55KSI	80 KSI
Inlay weld (MIL-4N1A or MIL-8N12)	9 KSI	55KSI	80 KSI

TABLE 7: STRESS RESULT OF TURBINE AT 100% LOAD

100% Load Case Temperature of 743 °F, pressure of 280 PSI			
Component	**Maximum Von Mises Stress**	**Yield Stress**	**Tensile Stress**
Plug (Inconel 600)	16 KSI	31KSI	91 KSI
Casing (Cr-Mo Steel)	12 KSI	40 KSI	70 KSI
Filler Weld (MIL-RN82)	14 KSI	55KSI	80 KSI
Inlay weld (MIL-4N1A or MIL-8N12)	8 KSI	55KSI	80 KSI

As shown in Tables 4 thru 7, maximum stresses do not increase with load, and are well below yield. The stresses are highest at 25% load. This is because the difference in the coefficient of thermal expansion between the steel and nickel components is greatest at this load. See Table 4. The location and direction of the maximum principal stresses identified in the plug were consistent with the circumferential cracking shown in Figures 1, 2, and 3. The direction of the maximum principal stresses identified in the inlay were not consistent with the radial cracking shown in Figure 3. Consequently, their cause is not stress due to steady state operation.

Fatigue life determination requires knowledge of the amplitude of alternating stress cycles experienced by the component. Start-up, warm-up, on-line operation and cool down conditions must all be known to develop the operating histogram. In the case of this SSTG, little is actually known but the steady-state thermal conditions. The on-line alternating stress amplitude can be estimated if an average generator load is assumed. Ship sea trial data indicates the average generator load is approximately 50% of rated load. The approximate alternating stress is the difference between the stress at 50% load and the stress at either the 25% or 100% loads, whichever is greater. Referring to Tables 4 and 5, the maximum alternating stress is developed in the inlay, and is only 2 KSI. The ASME Boiler and Pressure Vessel Code, Section VIII, Division 2 provides fatigue design data for nickel-base alloy weldments in Table 3.F.4 (Curves B or C) and Table 3.F.10. The assumed alternating stress of 2 KSI should permit greater than 1.0 x $10^{\wedge 11}$ on-line operating cycles before any cracking begins. This further reinforces the conclusion that the circumferential cracks in the plug were due to welding, and the suspicion that the radial cracks in the inlay are due to increased thermal stress during warm-up and cool down. The thermal stress experienced during start-up, warm-up and cool down cycles is expected to be considerably greater than the on-line stress, which will reduce fatigue life considerably. Unfortunately, the required time and temperature data is not available to permit accurate calculations. For this reason, a fracture analysis and "leak-before-break" analysis is necessary to determine cycles to failure and type of failure by modeling selected flaws in the weld.

Nonetheless, a transient of 0% to 25% generator load (start-up) was studied. However, since there was limited technical manual data available for this loading condition, many engineering assumptions were applied. The key unknown factor is the rate of turbine casing temperature change with time, and the corresponding temperature gradient across the casing wall. A 0% to 25%, load transient was modeled from room temperature (72°F) to 25% operating load temperature (646°F) on the inner surface of the casing. For the warm-up time, 30 seconds and 200 seconds were used as a comparison. This large temperature variation resulted in a spike of thermal stress. The sudden rise of stress is known as "thermal shock" which is a prime contributor to material fatigue. The analysis concluded that maximum stress of the turbine casing with 30 seconds warm up time resulted in more than twice of the stress of the 200 seconds warm up time. The analysis was repeated with a higher initial temperature of 300°F. The result was that maximum stresses in the 30 seconds case are approximately three times more than the 200 seconds case. This finding indicates that a more controlled warm up procedure is probably necessary to limit thermal stress at the bimetallic weld, in order to prevent cracking and extend turbine material life. The current SSTG turbine start-up Engineering Operating Procedure (EOP) only specifies lube oil temperature requirements prior to turbine operation. Turbine casing warm up and thermal stresses are not taken into consideration with the current EOP. The actual turbine casing warm-up time and thermal distribution in way of the plugs for the current EOP needs to be measured by instrumenting the SSTG casing plug area with thermocouples and strain gages on both sides of the casing to measure actual thermal response. The data obtained from this testing would serve the following purposes:

1. Determine the feasibility of developing a modified start-up EOP that will minimize thermal shock. Due to the small size of these casings, a controlled start-up EOP may not be realistic given the existing trip throttle valve and governor start-up characteristics.

2. If the test data indicates the feasibility of developing a slower/more controlled start-up EOP, these test results would be used to back fit into the FEA model in order to both enhance stress predictions and optimize the EOP start-up procedure.

3. Additional FEA using thermal test data should provide answers as to why radial cracks initiated and if radial cracks could reform in repaired plug weldment inlays.

IMPROVED PLUG DESIGN STUDY

As an improvement for the current plug design, a feasibility study of plugs with various geometric shapes was performed. The FEA results of the original plug design were used as a standard to determine the best plug geometry. Original and improved plug designs are shown Figures 15, 16, 17, and 18, below:

FIGURE 15: ORIGINAL PLUG DESIGN

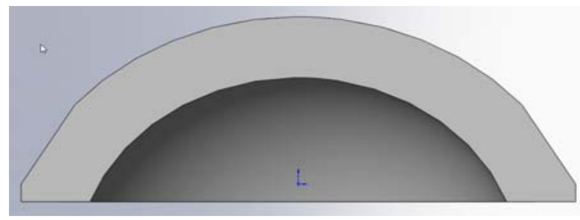


FIGURE 16: CONCAVE OUTWARD PLUG DESIGN

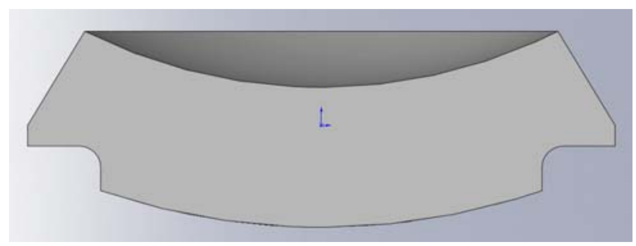


FIGURE 17: CONCAVE INWARD PLUG DESIGN

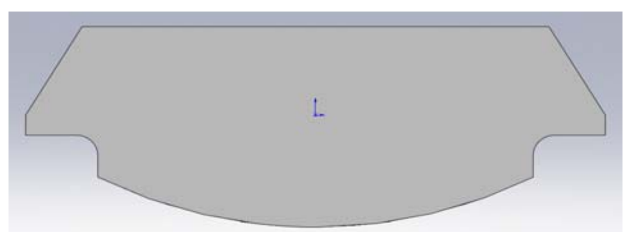


FIGURE 18: CONCAVE INWARD REINFORCED PLUG DESIGN

The original plug design was used as a standard. The intention of both the concave outward and inward plug designs was to convert some of the bending stress into hoop stress, thus reducing the stress on the weld. The concave inward reinforced plug design also allows for more material, which increases the overall strength of the design. Only pressure loads were modeled in this feasibility study. This study was further improved by varying the included curvature of the concave feature(s) of each design.

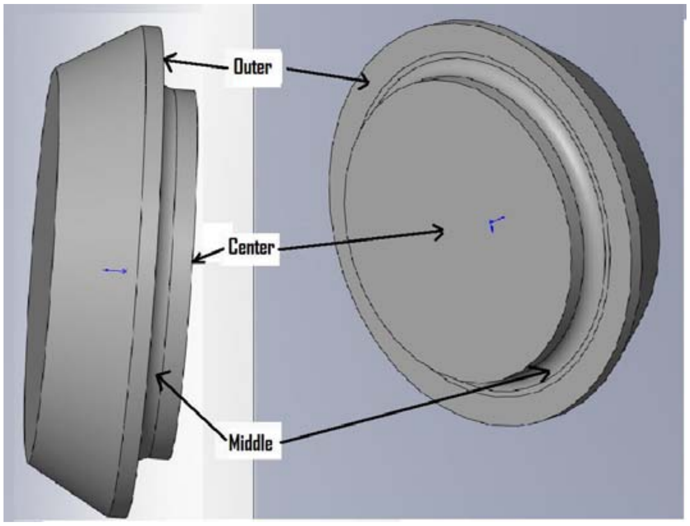


FIGURE 19: AVERAGE STRESS OF THE PLUG ON SELECTIVE AREA

The average stress values were taken at the center, middle and outer area of the plug inner surface which is the pressurized side (See Figure 19). Summary tables of all the FEA results are presented below (See Table 8). A maximum stress value is also recorded for the entire plug inner surface. The stress result for the original plug is highlighted in gold. Plug designs with stress values lower than the original design are highlighted in yellow for comparison.

Final Design Selection

From Table 8, the concave outward plug design highlighted in gray resulted in lower average stress at the middle and outer plug surface compared to the original design. Maximum stress, which appeared at the weld attachment area of the plug, indicated 24% lower stress than the original. This is important, since the cracks in the plug occurred here. The concave outward plug design diffuses stresses from the weld attachment (potential crack initiation site) and re-concentrates it to the center. This design transfers some of the bending stress into hoop stress (See Figures 20 and 21 for a graphical representation of the mechanical stress distribution). The curvature should also provide some flexibility, which should help reduce thermal stresses. The concave outward design could be used in future repairs should the cracking reoccur. See Figure 22 for a conceptual 3D representation of the concave outward plug.

TABLE 8: SUMMARY TABLE OF FEA STRESS STUDY RESULT ON THE PLUG (UNIT PSI)

	Average Stress (psi)		Average Stress (psi)		Average Stress (psi)		Average Stress (psi)		Max Stress	
Original	**Whole Plug**	**% Diff**	**Center**	**% Diff**	**Middle**	**% Diff**	**Outer**	**% Diff**		**% Diff**
(No Curvature)	1286.58	0	996.082	0	1483.22	0	1800.29	0	9926.03	0
Concave Outward	**Whole Plug**		**Center**		**Middle**		**Outer**			
Less Curvature	1434.93	11.5	1367.13	37.3	1311.46	-11.6	1616.35	-10.2	7003.52	-29.4
|	1280.66	-0.5	1090.09	9.4	1301.77	-12.2	1604.25	-10.9	7481.23	-24.6
|	1434.93	11.5	1367.13	37.3	1311.46	-11.6	1616.35	-10.2	7003.52	-29.4
|	1761.54	36.9	1938.91	94.7	1358.02	-8.4	1623.93	-9.8	5157.95	-48.0
More Curvature	2310.98	79.6	2836.93	184.8	1423.81	-4.0	1603.09	-11.0	4761.54	-52.0
Concave Inward	**Whole Plug**		**Center**		**Middle**		**Outer**			
Less Curvature	1518.17	18.0	1368.49	37.4	1739.35	17.3	2009.6	11.6	9458.58	-4.7
|	1578.44	22.7	1443.86	45.0	1803.21	21.6	2023.84	12.4	9840.35	-0.9
|	1676.81	30.3	1557.78	56.4	1918.16	29.3	2069.63	15.0	9205.51	-7.3
More Curvature	1818.82	41.4	1701.38	70.8	2148.85	44.9	2064.65	14.7	8008.76	-19.3
Concave Inward Reinforced	**Whole Plug**		**Center**		**Middle**		**Outer**			
Less Curvature	1288.3	0.1	1084.98	8.9	1575.73	6.2	1786.42	-0.8	9048.45	-8.8
|	1314.44	2.2	1066.51	7.1	1562.6	5.4	1728.12	-4.0	8974.92	-9.6
|	1294.68	0.6	1076.66	8.1	1607.92	8.4	1803.9	0.2	9060.09	-8.7
More Curvature	1317.55	2.4	1088.67	9.3	1671.9	12.7	1792.5	-0.4	8849.56	-10.8

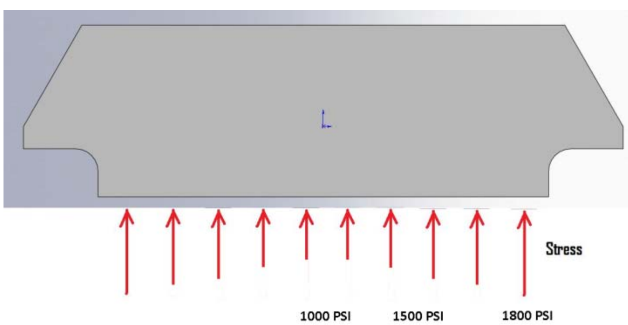


FIGURE 20: GRAPHICAL REPRESENTATION OF MECHANICAL STRESS DISTIBUTION FOR ORGINAL PLUG

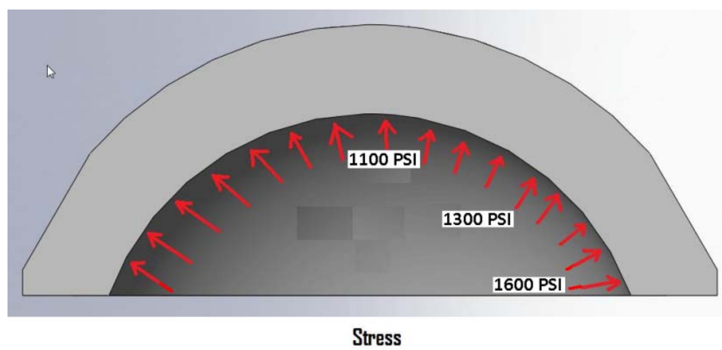


FIGURE 21: MECHANICAL STRESS DISTRIBUTION FOR CONCAVE OUTWARD PLUG

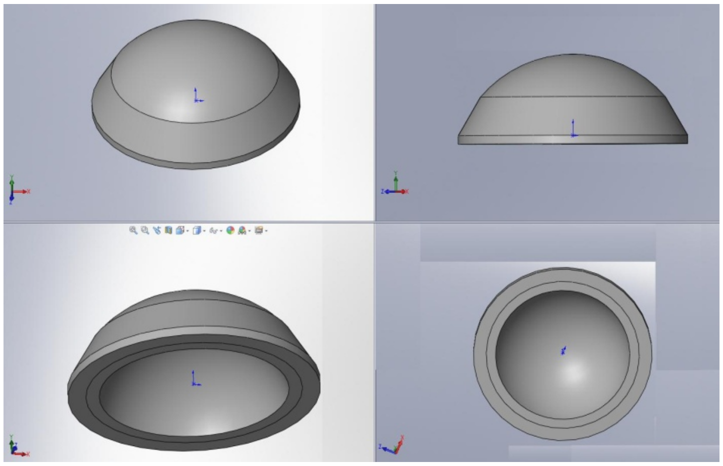


FIGURE 22: CONCAVE OUTWARD PLUG DESIGN 3D VIEW

FRACTURE ANALYSIS

A fracture/fatigue analysis of flaws found in SSTG plug welds was performed as reported in reference (6). The fatigue and fracture analysis of remaining flaws in the plug welds assumed "worst case scenario" loading conditions (yield stress). The analysis focused on the plug replacement repair with minor inclusions in the welds to evaluate the possibility of defect growth under assumed conditions. Based on service loads, defect behavior, such as failure mode and time to failure can be obtained using the techniques described below.

Fracture Analysis Assumptions and Background

1. Fatigue crack growth and fracture toughness values for SSTG fabrication materials were obtained from subject technical literature and used as a comparison to the calculated value.

2. A closed-form stress intensity solution approximating the flaws found in the SSTG plug welds was used in this analysis, see Figure 23.

3. Cracks were assumed to propagate within a single material and not from one material into another.

4. Analysis results were checked with AFGROW (fatigue crack growth software tool), per references (6) and (7).

Fracture Analysis Calculation

1. Analysis was preformed as if the crack grows all the way through the SSTG casing thickness (~1-in).

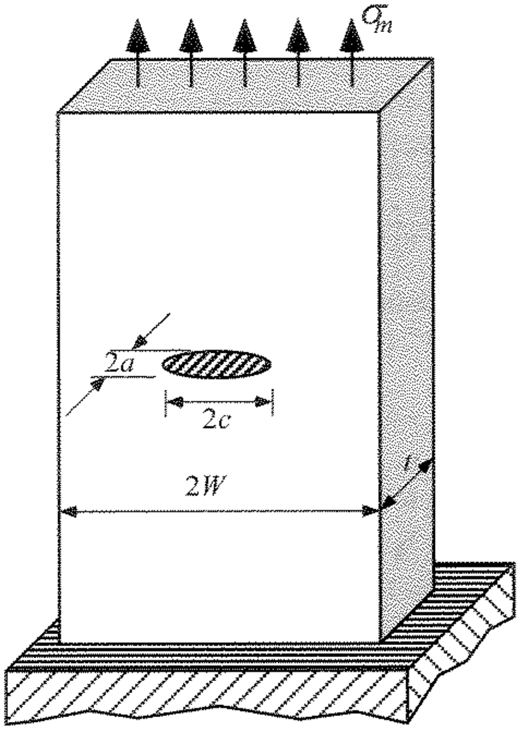
2. Based on the radial cracks found during the repairs, three crack lengths were studied: 1/8 inch, 1/4 inch, 3/8 inch.

3. Analysis was performed on Inconel 600 and X-750, the filler weld (MIL-RN82) and cast Cr-Mo steel casing.

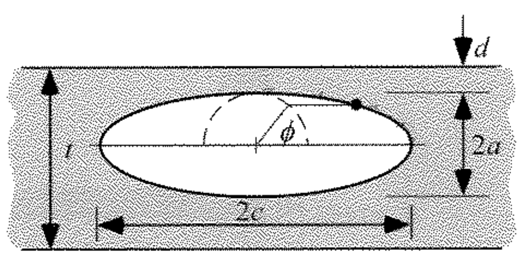
4. Membrane stress (σ_m) was held at material yield stress (worst case scenario).

5. Stress intensities were calculated for each flaw in each material, if calculated value was less than the material fracture toughness value a "leak-before-break" condition exists.

Stress-Intensity Solution for an Elliptical Buried Flaw in a Flat Plate



σ_m - Membrane (tensile) stress



$$K_I = \sigma_m F \sqrt{\frac{\pi a}{Q}}$$

where

$$F = (M_1 + M_2\lambda^2 + M_3\lambda^4) g f_\phi f_w$$

$$\lambda = \frac{a}{a+d}$$

$$f_w = \left[\sec\left(\frac{\pi c}{2W}\sqrt{\frac{2a}{t}}\right)\right]^{1/2}$$

$$M_2 = \frac{0.05}{0.11 + \left(\frac{a}{c}\right)^{1.5}}$$

$$M_3 = \frac{0.29}{0.23 + \left(\frac{a}{c}\right)^{1.5}}$$

$$g = 1 - \frac{\lambda^4\sqrt{2.6 - 2\lambda}}{1 + 4\lambda} |\cos\phi|$$

For $a/c \le 1$:

$$Q = 1 + 1.464\left(\frac{a}{c}\right)^{1.65}$$

$$f_\phi = \left[\left(\frac{a}{c}\right)^2 \cos^2\phi + \sin^2\phi\right]^{1/4}$$

$$M_1 = 1$$

For $a/c > 1$:

$$Q = 1 + 1.464\left(\frac{c}{a}\right)^{1.65}$$

$$f_\phi = \left[\left(\frac{c}{a}\right)^2 \sin^2\phi + \cos^2\phi\right]^{1/4}$$

$$M_1 = \sqrt{\frac{c}{a}}$$

FIGURE 23: ILLUSTRATION OF CLOSED FORM STRESS INTENSITY SOLUTION, REFERENCES (8) AND (9)

Fracture Analysis Result

As shown in Table 9, the analysis results indicated that a “leak-before-break” condition exists for each material under the conditions described above. This means that if an existing flaw were to propagate in the current repair, steam leakage would appear before catastrophic failure would occur. Case studies were performed on each of the four SSTG fabrication materials (Cr-Mo steel casing, Inconel X-750 (original plug), Inconel 600 (replacement plug) and MIL-RN82 weld filler metal) and 3 crack sizes (1/8 inch, 1/4 inch and 3/8 inch) using fracture toughness values for each material at elevated temperatures in air or water, when available, to closely approximate the hot steam environment contained by the SSTG casing. As this analysis was performed at stresses well above the SSTG operating envelope, these results shows that the current plug replacement weld repairs that may contain small inclusions are likely to be safe and reliable. AFGROW fatigue crack growth analysis software calculations also confirmed this conclusion.

TABLE 9: FRACTURE ANALYSIS CASE STUDY RESULTS

Crack Depth "2a" (inch)	Crack Length "2c" (inch)	Crack Aspect Ratio (depth/length)	Calculated K (KSI(inch^0.5))			σ_{YS} (KSI)	K_{JC} (KSI(inch^0.5))	
			ϕ = 0°	ϕ = 45°	ϕ = 90°			
1.000	0.125	8.0	15	14	6	40 (min)	78	Cr-Mo Steel (1000°F Air)
	0.250	4.0	21	19	13	40 (min)		
	0.375	2.7	26	23	19	40 (min)		
1.000	0.125	8.0	31	27	13	81	147	IN X-750 (800°F Air)
	0.250	4.0	43	39	26	81		
	0.375	2.7	52	48	38	81		
1.000	0.125	8.0	12	11	5	31	262	IN 600 (640°F Air/Water)
	0.250	4.0	17	15	10	31		
	0.375	2.7	20	18	14	31		
1.000	0.125	8.0	21	19	9	55	365	EN82 Weld Metal (129-640°F Air)
	0.250	4.0	29	26	17	55		
	0.375	2.7	35	32	26	55		
1.000	0.125	8.0	20	18	16	55	335	EN82 Weld Metal (640°F Water)
	0.250	4.0	29	26	17	55		
	0.375	2.7	35	32	26	55		

Fatigue Crack Growth Analysis. Literature values for fatigue crack growth resistance of Inconel 600, Inconel X-750, and Cr-Mo steel were used to estimate the number of cycles for a crack to grow through the casing thickness. MIL-RN82 crack growth data is not available, but can be assumed to be similar to Inconel 600, based on its high toughness. Notional buried flaws were seeded in the center of the SSTG casing and allowed to grow to the surface. The load range used for this calculation ranged from zero stress to material yield stress, which is well above service loading, and considered to be a worst case scenario.

Table 10 gives the results of the fatigue crack growth analysis, including the number of cycles required for embedded cracks to grow from an assumed 0.25-in flaw, remaining after repairs, through the entire SSTG casing thickness (1-in). Under the assumed conditions described above, the Inconel 600 material used in the replacement plugs requires approximately 187,702 cycles to fail, whereas the original Inconel X-750 material only needed 8,319 cycles. Therefore, the newly installed Inconel 600 plugs are 23 times more resistant to fatigue crack propagation than the original Inconel X-750 plugs.

An estimate of time to fatigue failure can be made for ships operating with welded over inclusions in the generator turbine casing inlay, based on the findings above. The earliest repair performed with welded over inclusions was in 2009. If the current repair is 23 times more resistant to crack propagation, the time to failure could be as much as 184 years. In view of the fact that the projected remaining life of the class is only 31 years, it is not likely that a remaining flaw will propagate entirely through the casing wall during the life of the ship.

TABLE 10: FATIGUE GROWTH RESULT

Material	Cycles to Grow Through Thickness
Cr-Mo Steel (1000°F Air)	277,279
Inconel X-750 (800° Air)	8,139
Inconel 600 (640° Air/Water)	187,702

CONCLUSIONS AND FUTURE WORK:

1. Welding-related strain age cracking or hot cracking were considered the likely mechanisms that drove the circumferential cracking in the heat affected zone of the Inconel X-750 plug. NNSY's plug replacement repair procedure incorporated actions to minimize both of these mechanisms.

2. The radial cracks found in the inlay during repairs could not be metallurgically analyzed for cause of failure, because doing so would have destroyed the effectiveness of the inlay. The cause of these cracks is suspected to be thermal stress during warm up and cool down, because the stresses calculated by FEA during steady state operation are too low, and in the wrong direction to be the cause.

3. The FEA at steady-state turbine temperatures concluded that the location, magnitude and direction of the stresses were consistent with the circumferential cracking actually noted in the plug. The analysis also showed that a rapid turbine start-up procedure can cause high stress at the plug and weld. High thermal stress can induce cracks to develop or propagate.

4. The feasibility analysis of different design plugs showed that a concave outward shape can reduce the stress at the heat affected zone of the plug to inlay weld by approximately 24%.

5. The fracture analysis of the plug replacement weld repair with minor inclusions in the inlay concluded a “leak-before-break” condition as the mode of failure. “Leak-before-break” means if a crack were to propagate through the turbine casing wall, steam leakage will occur well before catastrophic failure happens.

6. As a follow-up effort, another study was conducted to determine number of cycles required for a crack to grow through the turbine casing wall. This study showed that the current plug material (Inconel 600) is much more resistant to crack growth than the original plug material (Inconel X-750). The large number of cycles indicates that operating time in excess of the projected remaining life of the ship likely will be required for cracks to propagate through the casing wall.

7. If future plug repair is required, then the use of the new concave outward design plug is recommended to reduce stress at the weld based on the detailed design study.

8. A study of SSTG casing warm-up time and thermal distribution by thermocouple and strain gage instrumentation is recommended to measure the material response. Due to the small size of SSTG, a controlled start-up procedure may not be realistic given the existing trip throttle valve and governor start-up characteristics. This must be assessed by actual testing. The data obtained from this testing would serve the following purposes:

a. Determine the feasibility of changing the EOP to limit excessive thermal transients.

b. This test data will be used in the existing FEA model in order to both enhance stress predictions and optimize the EOP start-up procedure if possible.

c. The additional FEA using thermal test data may provide answers as to why radial cracks initiated and if radial cracks could reform in repaired plug weldment inlays.

9. If possible with the existing trip throttle valve and governor, develop a revised start-up EOP to reduce excessive thermal transient.

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